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BIMETALLIC CAST IRON ROLLS – SOME APPROACHES TO ASSURE THE EXPLOITATION PROPERTIES

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Original scientific paper

The study represents a detailed approach of the influence of some technological factors on durability in exploitation of rolling mill iron rolls and suggests solutions meant to increase the durability of the rolls in exploitation. These researches are trying to give answers to most of the actual problems related to the increase of hardness of rolling mill rolls. These results are of immediate practical utility both for the cast-iron rolling mills roll manufacturing industry and the rolling sectors. In this sense, these research results can be used in the collective framework of the foundries and the rolling mills sectors for quality assurance of rolls as far back as the phase of production to their exploitation, what leads to, inevitably, the quality assurance of produced laminates. Genuine casting technical conditions are analyzed in order to increase the rolls' resistance to wearing, decrease the conversion costs and reduce the waste, decrease the labor costs by lowering the richly alloyed iron with nickel, chromium and molybdenum consumption. Using the new research technique – the numerical simulation – statistical and mathematical data, registered when elaborating the cast iron type FDId2 destined to cast the hard crust of the large-diameter bimetallic rolls, were processed within the present research. The purpose is the optimization of the chemical composition as an influential factor on the rolls hardness, thus, implicitly, on their exploiting qualities. The realization of an optimal chemical composition can constitute a technically efficient mode to assure the exploitation properties, the rolling mills rolls material having an important role in this sense. From this point of view the mathematical modeling is applied, starting from the differentiation on rolls component parts, taking into consideration the industrial data obtained in rolls-foundry, as well as the national standard specifications, which recommend the hardness for different chemical compositions. From this point of view the research is inscribed in the context of scientific capitalization of the process and the industrial technologies optimization, in the way of the analysis and the mathematical experiment.

Keywords: *bimetallic rolls, optimal chemical composition, quality assurance*

Valjci od bimetalnog lijevanog željeza – Neki postupci za osiguranje uporabnih svojstava

Izvorni znanstveni članak

U ovom se radu detaljno razmatra utjecaj nekih tehnoloških faktora na trajnost valjaoničkih željeznih valjaka i predlažu rješenja za povećanje izdržljivosti u uporabi. Istraživanjem se pokušavaju dati odgovori na najvažnije probleme u vezi povećanja tvrdoće valjaka. Dobiveni rezultati su od neposredne praktične koristi kako za proizvođačku industriju valjaoničkih valjaka od lijevanog željeza tako i za valjaoničke odjele. U tom se smislu ovi rezultati mogu koristiti u ljevaonicama i valjaonicama za osiguranje kvalitete valjaka sve od faze proizvodnje pa do uporabe, što neizbježno vodi do osiguranja kvalitete proizvedenih laminata. Analiziraju se stvarni tehnički uvjeti lijevanja kako bi se povećala otpornost valjaka na trošenje, smanjili troškovi konverzije i reducirao otpad, smanjili radni troškovi smanjivanjem bogato legiranog željeza s potrošnjom nikla, kroma i molibdena. Korištenjem nove metode istraživanja – numeričke simulacije – obradili su se statistički i matematički podaci zabilježeni kada se elaborirao željezni lijev tipa FDId2 namijenjen lijevanju tvrde kore bimetalnih valjaka velikog promjera. Svrha je optimizirati kemijski sastav kao faktor od utjecaja na tvrdoću valjaka, a tako implicitno i na njihova uporabna svojstva. Postizanje optimalnog kemijskog sastava može predstavljati tehnički efikasan način za osiguranje uporabnih svojstava budući da materijal valjaka ima u tom smislu važnu ulogu. Primijenjena je matematička metoda počevši od diferenciranja sastavnih dijelova valjaka, uzimajući u obzir industrijske podatke dobivene u ljevaonici valjaka, kao i specifikacije nacionalnog standarda koji preporučuje tvrdoću kod različitih kemijskih sastava. U tom smislu ovo istraživanje može pridonijeti optimiziranju industrijskih tehnologija analizom i matematičkim eksperimentom.

Ključne riječi: *bimetalni valjci, optimalni kemijski sastav, osiguranje kvalitete*

1 Introduction Uvod

Although the manufacture of rolls is in constant improvement, the requirements for superior quality rolls have not yet been completely satisfied, in many cases the absence of quality rolls preventing the realization of quality laminates or of productivity of which rolling mills are capable.

In the selection of materials several factors have to be considered including the type of rolling mill, the size of rolls (of specially this diameter), the speeds of lamination, the stands from the train of lamination for which the rolls are achieved, the working temperature in the lamination process, the module of cooling during work, the size caliber, the pressure on rolls, the rolled material hardness, etc.

The choice of material for rolls is the operation which takes into consideration the own solicitations of the lamination process afferent to the type of laminates (half-product or the finite laminate), and the features of different materials considered optimal in the fabrication of different typo-dimensions of rolls.

The large diversity of the laminated products and the various work conditions has determined the creation of an extremely large portfolio of rolls. The existence of this particular diversity in the manufacturing of rolls refers both to dimensions and structures, hardness, fields of utilization.

When choosing the right rolls, besides technical and work conditions issues, the endurance of the rolls within exploitation is of great importance (resistance to tear and breakage). In order to obtain maximum endurance of the rolls an optimal correlation between the exploitation conditions and quality has to be established.

Their different shape, work surface quality, resistance to tear, hard working conditions (high and non-uniform pressures, non-uniform heating, mechanical and thermo shocks, combined mechanical efforts: bending, stretching, compression, traction) and non-uniform imposed metallurgic structure, raise important issues on the handling of the manufacturing technologies. Thus, for obtaining the desired quality through correlation of the elements intervening in the manufacturing (elaboration – forming – casting – thermal treatment), knowing the working conditions is a must.

Durability in the rolls exploitation is determined by their resistance to wear which does not depend only on the quality of the alloy they are made of, but also on the brand of the laminated alloy, as well as on the means and conditions in which they work. The rolls usually tear in a setting where the determinations are made according to the minimal thickness of the working crust that is removed by returning (welding and returning, rectification, and so on) in order to re-establish the initial profile of their surface. Although wearing during the laminating process is a normal phenomenon, this can be managed by creating some conditions that will lead to its decrement. The higher the hardness of the rolls working crust, the more reduced the wearing is. Yet there is no direct dependency between these two characteristics. Usage of rolls with higher hardness, along with the intense removal of the iron doss and oxides from the laminated surface, leads to increased hardness during their exploitation.

2 The influence of chemical composition and structure on the rolls hardness

Utjecaj kemijskog sastava i strukture na tvrdoću valjaka

The chemical composition of the alloy used to cast rolls is one of the main factors that contribute to the obtaining of the usage properties. After an eventual processing in liquid state, a modifying in directional conditions of solidification and cooling, and, in some cases, after thermo treatment, this determines the macrostructure and microstructure.

For high-quality rolls lamellar cast iron or nodular cast iron are used, alloyed with Cr, Ni and Mo. Of the common elements, S and P are limited to as small amounts of content as possible, according to the available raw material or the type of cast iron used. Only in the case of non alloyed lamellar cast iron, the increase of the P percentage up to 0,5 % is utilized (less and less often) in order to avoid cracking and to obtain a clean neck surface.

The cast iron structure (base metallic mass and the graphite inclusions) on the working surface constitutes the criteria that best characterize the functioning rolls behavior. Thus, the micro and macrostructure of the rolls are after ensuring the quality requested by the exploitation and is reached by the nature and chemical composition of the cast metallic alloys, different cooling speed and by the casting process. All these particularities imprint a specific macro and microstructure to each roll.

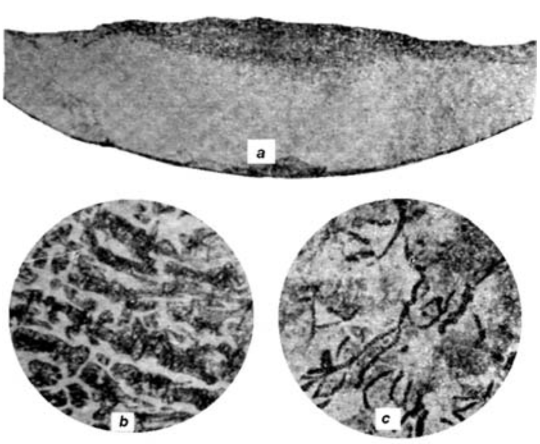

Figure 1 *The bimetallic rolls microstructure, alloyed with Cr, Ni and Mo, 70 HSh (100:1, nital attack 3 %). a – the alloys microstructure; b – the hard crust (cementite and martensite); c – the rolls core (perlite and graphite)*

Slika 1. *Mikrostruktura bimetalnih valjaka, legirani s Cr, Ni i Mo, 70 HSh (100:1, napad nitala 3 %). a – mikrostruktura legura; b – tvrda kora (cementit iI martenzit); c – jezgra valjka (perlit i grafit)*

The chromium capacity to maintain hardness on the entire section of the piece is important when producing profile rolls where a small flop of hardness on the depth of the mechanically made calibers. Profile rolls are, regularly, alloyed with contents of chromium between 0,6...1,5 %, no matter their type. In these cases nickel is usually added with contents by 0,2...0,3 % higher than chromium. Such a ratio between chromium and nickel ensures equalizing of the hardness on the rolls section and, at the same time, the decrease in their fragility.

Regarding the influence of nickel in liquid cast iron, this belongs to the group of graphitizing elements, but this influence is not considered in cast iron foundries. In this case, the fact that nickel, possessing unlimited solubility, allows the improvement of a series of exploitation properties of the cast piece, is of a higher importance. It determines increased resistance of the ferrite in the perlite, increases the mechanical resistance and resistance to wear of the iron cast rolls. Its main characteristic is that within certain limits, properly determined, it increases the hardness of the base metallic mass, by decreasing the critical point of eutectoid transformation. Because of this, even in massive pieces such as the rolls, under normal cooling conditions, one can obtain the entire range of transition structures (depending on the nickel content), not only in the hard crust, but in their entire section, from fine lamellar perlite to martensite with areas of non-decomposed austenite and, thus, due to it, a wide range of hardness 68 ... 88 HSh.

The influence of molybdenum is manifested only in contents higher than 0,6 % Mo. At contents lower than 0,6 % Mo, under the condition of maintaining the ratio between the structural components, dense structures with fine granulation are formed in the entire rolls area, both in its center and in the core and necks. Thus, higher resistance to wear and high temperatures of the hard crust, mechanical resistance and durability in exploitation of the rolls is obtained. Even at low contents the molybdenum dissolves in the perlite ferrite and causes increased resistance of the base metallic mass and thus the global rolls resistance.

In bimetallic rolls alloyed with contents higher than 3,8 % Ni and 0,8 % Cr, small graphite inclusions usually appear in hard crust. Even the most reduced amounts of silicon and high amounts of chromium in cast iron cannot stop the graphitizing process in the highly nickel alloyed cast iron, when maintaining the pieces in the temperature range of 900...950 °C. The presence of a sufficient molybdenum quantity determines the cessation of this decomposition. That is why the lamellar graphite rolls alloyed with chromium, nickel and molybdenum distinguish themselves by a higher hardness, thus having higher resistance to wear.

3 Establishing the optimal field through mathematical modeling

Stvaranje optimalnog polja matematičkim modeliranjem

A special category of rolls, that would best respond to the economic requirements, are those manufactured in bimetal version (obtained through casting of two types of alloys), with a very hard surface area and the core with high resistance to wear and bending strains. In this way, rolls with working surface hardness up to 100 HSh can be manufactured, thus being more resistant to wear than the rolls manufactured using one alloy. Bimetallic rolls cast from various qualities of cast iron hold a rather important place in the manufacturing of the rolls destined for various rolling-mill stands. In Fig. 2 the scheme of manufacturing is presented. The rolls are obtained by bimetal casting, in static version with core washing.

a)

b)

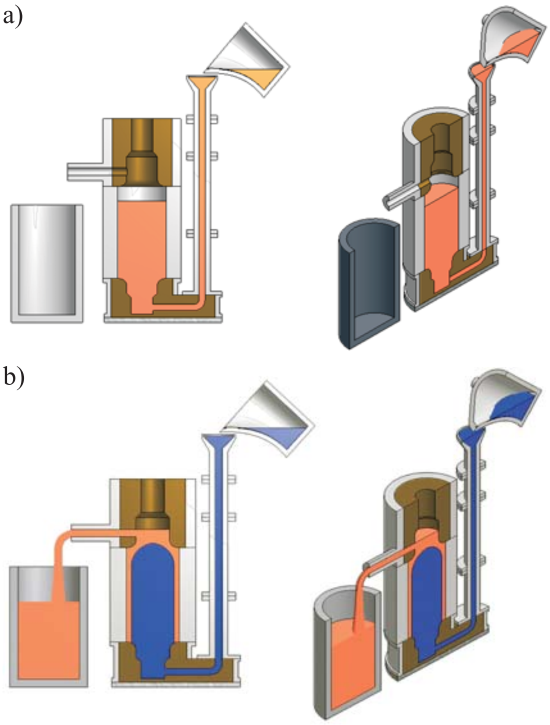

Figure 2 The bimetallic rolls casting scheme - a) phase I (rolls' body casting); b) phase II (rolls' necks and core casting)
Slika 2. Shema lijevanja bimetalnih valjaka - a) faza I (lijevanje tijela valjka); b) faza II (lijevanje vrata I jezgre valjka)

Table 1 Chemical composition of irons destined for bimetallic rolls hard crust casting
Tablica 1. Kemijski sastav željeza predviđenih za lijevanje tvrde kore bimetalnih valjaka

No.	Final chemical analysis, %							
	C	Si	Mn	P	S	Cr	Ni	Mo
1	3,250	1,910	0,410	0,132	0,030	1,610	3,460	0,320
2	3,190	1,380	0,430	0,124	0,019	1,520	3,210	0,350
3	3,200	1,190	0,420	0,112	0,037	1,320	3,360	0,360
4	3,250	1,220	0,350	0,122	0,035	1,340	3,220	0,350
5	3,200	1,130	0,400	0,122	0,030	1,490	3,020	0,300
6	3,210	1,370	0,410	0,114	0,021	1,420	3,040	0,400
7	3,210	1,220	0,480	0,117	0,020	1,350	3,120	0,370
8	3,190	1,260	0,700	0,118	0,025	1,330	3,370	0,150
9	3,240	1,360	0,270	0,119	0,020	1,420	3,200	0,230
10	3,300	1,240	0,600	0,120	0,021	1,390	3,240	0,350
11	3,200	1,150	0,520	0,120	0,023	1,430	3,280	0,330
12	3,040	1,080	0,520	0,112	0,016	1,280	3,030	0,400
13	3,220	1,240	0,520	0,118	0,016	1,360	3,030	0,340
14	3,200	1,200	0,500	0,120	0,018	1,380	3,280	0,400
15	3,280	1,280	0,300	0,121	0,024	1,480	3,070	0,430
16	3,210	1,210	0,560	0,118	0,030	1,380	3,450	0,430
17	3,180	1,060	0,550	0,121	0,024	1,280	3,290	0,410
18	3,230	1,240	0,510	0,118	0,016	1,390	3,630	0,420
19	3,200	1,140	0,660	0,118	0,024	1,120	3,460	0,420
20	3,240	1,240	0,510	0,112	0,028	1,350	3,460	0,410
21	3,120	1,240	0,550	0,118	0,030	1,580	3,110	0,370

Aided by the data on static casting version, by washing the core, of the bimetallic rolls, collected from the specialized rolls-foundry, Tab. 1 has been devised. Using the Matlab software a statistical-mathematical calculus has been performed so as to analyze the influence of the chemical composition on the bimetallic rolls crust's hardness affecting their exploitation durability.

For the 21 rolls (type FDId2, dimensions $D \times L$ ∅928x3300 mm) presented in Tab. 1, for the purpose of a statistical and mathematical calculus, their chemical compositions and hardness have been taken into consideration. The correlations resulting out of the calculus program are presented below both in analytical and graphic forms. The graphic representations are surfaces that present a stationary point, either an extreme point (maximal or minimal), or a saddle point, their coordinates often laying within the variable technological limits for independent parameters, respectively within the limits recommended by the standards for the dependent parameter, and other times far away from the technological limits, or even in the field where parameters values make no technological sense.

4
Variation of the bimetallic rolls crust hardness with the Cr, Ni and Mo contents
Varijacije tvrdoće kore bimetalnih valjaka mijenjanjem sadržaja Cr, Ni i Mo

To determine the hardness variation of the rolls crust (measured in Shore units – HSh) determined by the alloying elements content: HSh = HSh (Cr, Ni, Mo), the calculus program will determine the average values and the square average deviations, which are presented in Tab. 2.

Table 2 The average value and the square average deviation
Tablica 2. Prosječna vrijednost i prosječna devijacija na kvadrat

	Average value, %	Square average deviation
Cr	1,3914	0,10584
Ni	3,2538	0,17120
Mo	0,3591	0,06720
Hardness, HSh	66,143	3,66820

Next we present the results of the multidimensional processing of the experimental data. For this, a simulation has been searched of the dependent variable **u** related to the independent variables x, y, z, according to the general regression equation presented in formula (1). The optimal form for the simulation on a sample of 21 rolls (Tab. 1) is given by the regression hyper-surface equation (2) and the correlation coefficient would have the value rf = 0,7042, respectively the deviation from the regression surface is sf = 2,6051. This surface for the four-dimensional space admits a saddle point coordinates, presented in Tab. 3.

$$u = c_1 \cdot x^2 + c_2 \cdot y^2 + c_3 \cdot z^2 + c_4 \cdot x \cdot y + c_5 \cdot y \cdot z + c_6 \cdot z \cdot x + c_7 \cdot x + c_8 \cdot y + c_9 \cdot z + c_{10}. \quad (1)$$

$$\text{HSh} = -59{,}1863 \cdot \text{Cr}^2 - 30{,}5444 \cdot \text{Ni}^2 + 257{,}8439 \cdot \text{Mo}^2 - 72{,}9866 \cdot \text{Cr} \cdot \text{Ni} + 5{,}9368 \cdot \text{Ni} \cdot \text{Mo} - 353{,}5611 \cdot \text{Mo} \cdot \text{Cr} + 554{,}9472 \cdot \text{Cr} + 296{,}7692 \cdot \text{Ni} + 336{,}0614 \cdot \text{Mo} - 887{,}8065. \quad (2)$$

Table 3 The saddle point coordinates
Tablica 3. Koordinate točke prijevoja (saddle point)

Cr	Ni	Mo	HSh
1,6081	2,9771	0,41661	70,1748

The existence of this point inside the technological field is of great importance since it ensures a special stability to the process in the vicinity of this point, stability that is either to be preferred or avoided. It is observed that the values of chromium, nickel and molybdenum range within the standards, and the value of the hardness in the vicinity of the saddle point is according to the requirements of the rolls exploitation.

The regression hyper-surfaces behavior in the vicinity of the point where the three independent variables have average value can only be studied, by attributing the three independent variables values to the spheres concentric to the studied point. Since this surface cannot be represented in the four-dimensional space, each independent variable was replaced successively with its average value. Thus, the equivalent equations are presented in formula (3), (4) and (5).

$$HSh_{Cr\ med} = -30{,}5444\cdot Ni^2 + 257{,}8439\cdot Mo^2 + 5{,}9368\cdot Ni\cdot Mo + 195{,}2136\cdot Ni - 155{,}8937\cdot Mo - 230{,}2261. \quad (3)$$

$$HSh_{Ni\ med} = 257{,}8439\cdot Mo^2 - 59{,}1863\cdot Cr^2 - 353{,}5611\cdot Mo\cdot Cr + 355{,}3786\cdot Mo + 317{,}4628\cdot Cr - 245{,}5574. \quad (4)$$

$$HSh_{Mo\ med} = -59{,}1863\cdot Cr^2 - 30{,}5444\cdot Ni^2 - 72{,}9866\cdot Cr\cdot Ni + 428{,}0019\cdot Cr + 298{,}9008\cdot Ni - 733{,}9045. \quad (5)$$

The regression surfaces are rendered in Fig. 3, Fig. 5 and Fig. 7. By sectioning these surfaces with level planes (Fig. 4, Fig. 6 and Fig. 8), a more correct quantitative interpretation regarding the fair determining of the bimetallic rolls necks hardness value will be obtained by establishing the optimal variation field of the alloying elements. The analysis of the regression surface, represented in Fig. 3 and in Fig. 4, described by the equation (3), reveals that if the average value of the chromium content (1,39 %) is kept constant, for a content of 3,27...3,37 % Ni and 0,35...0,4 % Mo, maximal values of the hardness will be obtained. The minimal point of the hardness regression surface (64 HSh) must be avoided, by imposing lower limits both for the nickel content (3,25 %), and molybdenum (0,3 %).

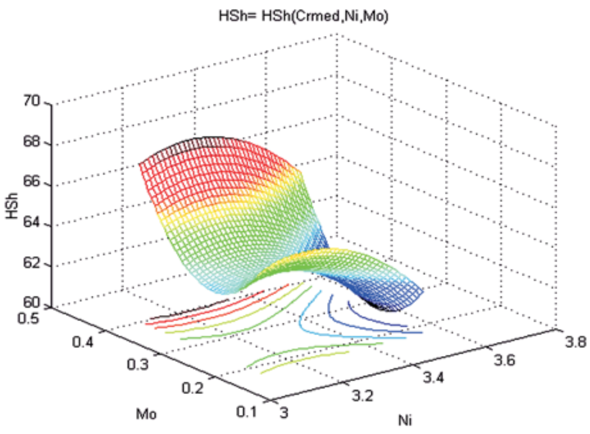

Figure 3 *Surface HSh = HSh (Cr_{med}, Ni, Mo)*
Slika 3. *Površina HSh = HSh (Cr_{med}, Ni, Mo)*

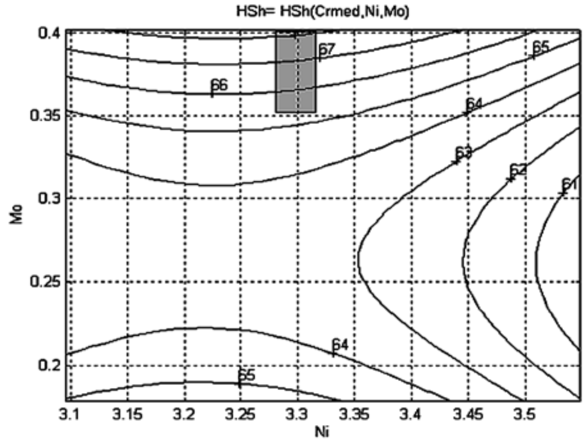

Figure 4 *The distribution contour HSh = HSh (Cr_{med}, Ni, Mo)*
Slika 4. *Krivulja distribucije HSh = HSh (Cr_{med}, Ni, Mo)*

By observing the quantitative representations in Fig. 5 and Fig. 6, of the regression surface described by the equation (4), we conclude that if the average value of 3,25 % Ni is kept constant, the hardness values of 70 HSh are to be obtained through a content of 0,15...0,25 % Mo and 1,45...1,55 % Cr. To avoid the hardness dropping there must be a limiting of Cr content to minimum 1,37 %, and the molybdenum values must not be higher than 0,3 %.

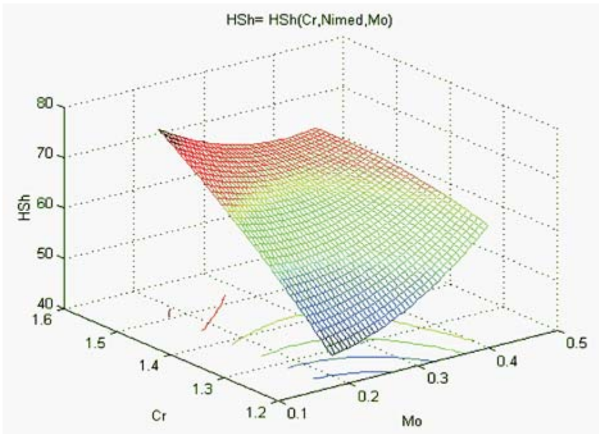

Figure 5 *Surface HSh = HSh (Cr, Ni_{med}, Mo)*
Slika 5. *Površina HSh = HSh (Cr, Ni_{med}, Mo)*

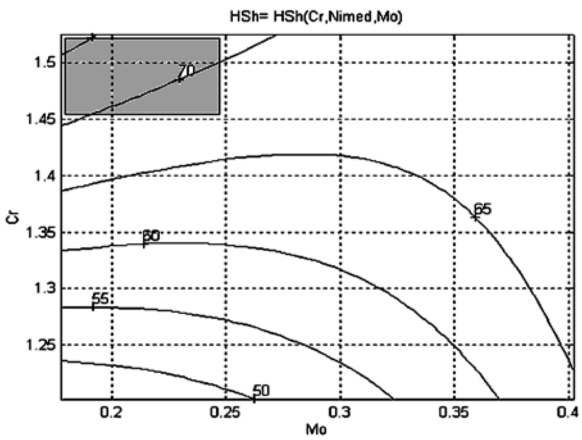

Figure 6 *The distribution contour HSh = HSh (Cr, Ni_{med}, Mo)*
Slika 6. *Krivulja distribucije HSh = HSh (Cr, Ni_{med}, Mo)*

The behavior of the regression surface, where the molybdenum value is kept constant (0,36 %) (Fig. 7 and Fig. 8), is described by the equation (5) which presents the point of maximum hardness at 68 HSh for 3,1...3,25 % Ni and 1,47...1,57 % Cr. The decrease of the chromium content doubled by the increase in nickel content leads to considerable diminution of the hardness values.

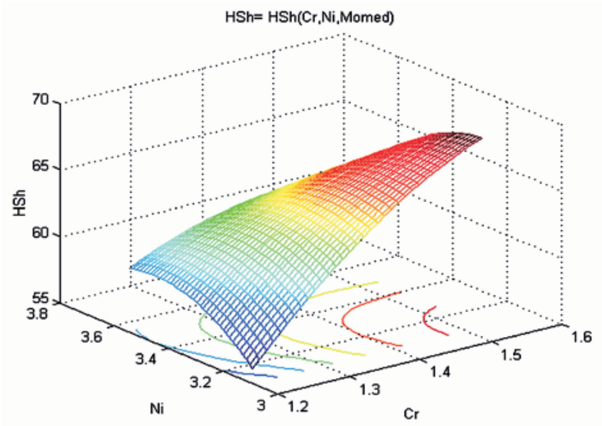

Figure 7 *Surface HSh = HSh (Cr, Ni, Mo_{med})*
Slika 7. *Površina HSh = HSh (Cr, Ni, Mo_{med})*

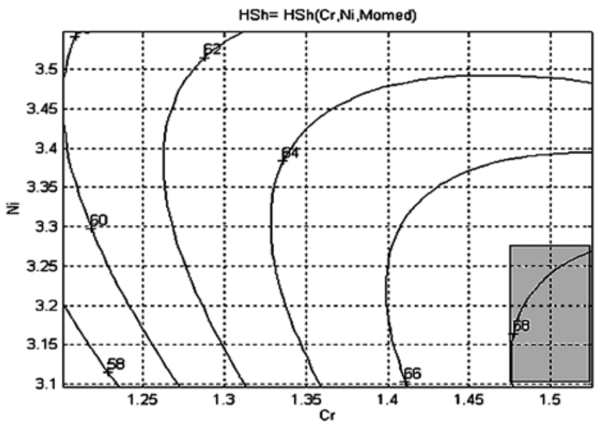

Figure 8 *The distribution contour HSh = HSh (Cr, Ni, Mo_{med})*
Slika 8. *Krivulja distribucije HSh = HSh (Cr, Ni, Mo_{med})*

Table 4 *The optimal alloyed elements limits*
Tablica 4. *Optimalne granice legiranih elemenata*

Cr, %	Ni, %	Mo, %
1,45 ... 1,55	3,25 ... 3,35	0,25 ... 0,35

As a whole we can conclude that for an optimal hardness it is necessary for the alloyed elements to align within the range presented in Tab. 4. These fields have been obtained by successively laying two of the ranges represented in the previous figures.

5 Conclusions
Zaključci

The analysis of the factors influencing the characteristics of the rolling rolls obtained by casting and, implicitly, their quality, has been done on the basis of a study regarding the following issues:

- the mechanical and thermo strains that the rolls are put to during their exploitation;
- influence of chemical composition and structure on hardness of the rolls' necks;
- use of the calculus programs in industrial processes and processing of the experimental data through statistics and mathematics.

The purpose of this study was the optimization of the chemical composition as a factor influencing the hardness of the rolls' necks, thus their durability in exploitation. As a result of this analysis the following conclusions can be drawn:

- taking into consideration the technical working conditions and the conditions of the rolls designed for laminations exploitation, these must have, besides hardness and resistance to wear, special mechanical properties to withstand the efforts they are exposed to during work. It is thus required for the roll to be elastic enough to sustain the bending efforts, and on the necks' surface, to a certain depth of the crust, to present a high level of hardness. This is accomplished by applying a manufacturing technology based on varied solidification and cooling speeds, doubled by the influence of the alloying elements (Cr, Ni, Mo), in the case of *monometallic casting*, respectively by using two qualities of cast iron, in the case of *bimetallic casting*.
- casting the *bimetallic rolls*, with high levels of hardness, the silicon content varies over a fairly wide range (0,25...0,80 %), according to the chromium content in the alloy. At 1,5...1,6 % Cr in lamellar graphite rolls and alloyed with chromium, nickel and molybdenum (with hardness of 72 HSh) and in rolls alloyed with chromium and nickel (hardness of 70 HSh) the regular silicon contents are found within the limits 0,35... 0,45 %. Decrease of the silicon content to 0,35 % in order to obtain a cleaner white area, often leads to the forming of a cold fissure, characteristic flaw of these specific rolls.
- when manufacturing bimetallic rolls with high level of hardness, the carburigen influence of the chromium is mostly used. In order to increase the core and axle pins' resistance these rolls are washed with gray cast iron. As such, the chromium content in the rolls axis decreases down to 0,3 %. In highly-alloyed bimetallic rolls of various types the chromium content can vary in wide ranges: 0,5...0,8 % to crust hardness of 70...85 HSh, respectively 1,2...1,5 % to an undefined structural crust and hardness of 75...88 HSh.
- almost all these rolls are cast out of cast iron alloyed with chromium and nickel. Nickel neutralizes the carburigen influence of chromium, and the increase of resistance obtained due to the nickel doubles to a ratio Ni/Cr 2:1.
- in contents of approximately 1,0 % Mo, when its carburigen action is manifested, the depth of the skip is increased and the free cementite areas are maintained on the entire surface of the roll. That is why, in rolls used for plate rolling, to avoid this disadvantage, the molybdenum content is limited to between 0,3...0,6 %. Casting rolls with molybdenum contents lower than 0,25 % is not rational, since it cannot lead to a visible improvement of their structure. Adding molybdenum in the cast iron for rolls represents one of the sure methods to increase resistance to wear and high temperatures, as well as the resistance on the whole.

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